(12)

R-2391-AF

April 1979

Aircraft Turbine Engine Monitoring Experience: Implications for the F100 Engine Diagnostic System Program

J. L. Birkler, J. R. Nelson

A Project AIR FORCE report prepared for the United States Air Force

Rand
SANTA MONICA, CA.

The research reported here was sponsored by the Directorate of Operational Requirements, Deputy Chief of Staff/Research, Development, and Acquisition, Hq USAF, under Contract F49620-77-C-0023. The United States Government is authorized to reproduce and distribute reprints for governmental purposes notwithstanding any copyright notation hereon.

Library of Congress Cataloging in Publication Data

Birkler, John L
Aircraft turbine engine monitoring experience.

([Report] - Rand Corporation ; R-2391-AF)
1. Airplanes--Turbojet engines--In-flight monitoring. 2. Airplanes, Military--Testing.
I. Nelson, John R., 1934- joint author.
II. United States. Air Force. III. Title.
IV. Series: Rand Corporation. Rand report ; R-2391-AF.
AS36.R3 R2391 [TL709.3.T63] 628.74'64 79-12415
ISBN 0-8330-0118-3

The Rand Publications Series: The Report is the principal publication documenting and transmitting Rand's major research findings and final research results. The Rand Note reports other outputs of sponsored research for general distribution. Publications of The Rand Corporation do not necessarily reflect the opinions or policies of the sponsors of Rand research.

Published by The Rand Corporation

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

14

1. REPORT NUMBER: RAND/R-2391-AF
2. GOVT ACCESSION NO.:
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): 6 Aircraft Turbine Engine Monitoring Experience: Implications for the F100 Engine Diagnostic System Program.
5. TYPE OF REPORT & PERIOD COVERED: 9 Interim rept. 1977-1978.
6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): 10 J. L. Birkler J. R. Belson
8. CONTRACT OR GRANT NUMBER(s): 15 F49620-77-C-0023
9. PERFORMING ORGANIZATION NAME AND ADDRESS: The Rand Corporation, 1700 Main Street, Santa Monica, California 90406
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 11 Apr 79
11. CONTROLLING OFFICE NAME AND ADDRESS: Project AIR FORCE Office (AF/RDQA), Directorate of Operational Requirements, Hq USAF, Washington, D.C. 20330
12. REPORT DATE: March, 1979
13. NUMBER OF PAGES:
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): 12 43p.
15. SECURITY CLASS. (of this report): UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

No Restrictions

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Aircraft Engines	Maintenance
Turbines	Cost Analysis
Monitors	Service Life
F100 Engine	Preventive Maintenance

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

See Reverse Side

296 600 Gw

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

A briefing report examining experience gained from six aircraft turbine engine monitoring system case studies and their implications for the F100 Engine Diagnostic System under development for the F-15 and F-16 aircraft. Emphasis is on the substance of the EDS program, how it relates to previous engine monitoring experience, and some policy options. Two case studies are presented in detail: The U.S. T-38 Engine Health Monitoring System and the British Engine Usage Monitoring System. Conclusions are: (1) Experience does not warrant optimistic near-term cost reduction. (2) The flight-test plan, as currently designed (October 1978), is unlikely to yield conclusive evidence on the value of the EDS. (3) The present scope of the EDS omits valuable long-term design feedback and potential improvement to testing cycles. Recommendations are: (a) develop a phased implementation schedule, (b) provide a continuous recording option, and (c) revise the life-cycle analysis to reflect more completely the costs and benefits of the EDS relative to both aircraft and engine. 43 pp. Refs. (DGS)

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PREFACE

This report documents a briefing on the findings of a study conducted for the Deputy Chief of Staff/Research, Development, and Acquisition (AF/RD) as part of the project "Methods and Applications of Life-Cycle Analysis for Air Force Systems," sponsored by Project AIR FORCE. The research was performed during late 1977 and the first half of 1978. The F100 Engine Diagnostic System (EDS) program characteristics are those of October 1978.

Research on the F100 EDS program was undertaken to enhance the understanding of how life-cycle analysis is being used in the Air Force to support system-acquisition decisions. Initially, the authors focused on the analytical methods and procedures employed in the EDS life-cycle analysis. When other important substantive issues in the EDS program became apparent, however, they expanded the inquiry to include experience gained on other engine monitoring systems and its implications for the F100 EDS program.

This report discusses but does not dwell on the issues of life-cycle analysis. The primary emphasis is on the substance of the EDS program, how it relates to previous engine monitoring experience, and some remaining policy options.

The study findings were presented in late 1978 and early 1979 to audiences in HQ USAF, the Air Force Systems Command, the Air Force Logistics Command, and the Tactical Air Command. The techniques developed in the study should also be of interest to other agencies as well as to a wider audience of analysts and decisionmakers concerned with aircraft turbine engine monitoring or with the broader topic of life-cycle analysis.

A Rand report now in preparation describes in greater detail the supporting research on experience gained from selected engine monitoring systems.

SUMMARY

This briefing report examines the experience gained from several aircraft turbine engine monitoring systems used over the last decade and a half and the implications of that experience for a new monitoring system--the Engine Diagnostic System--under development for the F100 engine on the F-15 and F-16 tactical fighter aircraft. The examination reveals that *two different approaches* to engine monitoring have evolved in attempts to achieve the goal of improved engine operations, maintenance, and management while reducing support costs. The first concentrates on short-term operations and maintenance aspects and is usually accomplished by recording inflight data in a snapshot mode, i.e., a few seconds of data either at predefined performance windows or when certain engine operating limits are exceeded. The second approach focuses on long-term design-oriented benefits through improved knowledge of the engine operating environment. To achieve the design-oriented benefits, data must be recorded continuously on at least a few aircraft at each operational location.

U.S. monitoring systems have focused on short-term, maintenance-oriented benefits, whereas the British have developed a system that has focused only on long-term, design-oriented benefits. From a life-cycle analysis viewpoint, it would seem that both types of benefits are worthy of consideration in any new monitoring system.

We have also reviewed ongoing engine duty-cycle research being conducted by the military services. This research has demonstrated that neither the services nor the engine manufacturers have had a clear idea of engine operational usage--i.e., of power requirements and transients on actual mission flight profiles--in fighter aircraft. As a result, engine parts life has generally been overestimated, and expected life-cycle costs have been understated. This situation has improved significantly during the past several years.

Much uncertainty exists about the benefits and costs attributable to engine monitoring systems. We believe that the maintenance cost savings used to justify the F100 EDS are unlikely to materialize over

the short term. But whether EDS passes or fails in the narrow sense of cost savings over the short term should not be the sole criterion on which it is judged. The potential benefits of anticipating needed maintenance, helping maintenance crews and engineering support personnel to better understand engine failure cause and effect, and verifying that maintenance has been properly performed have substantial value. These benefits are especially significant now that the Air Force is moving toward an on-condition maintenance posture, as is envisioned for the F100 engine. This engine is also of modular design, and so the EDS can be an important factor in achieving the maintenance-oriented engine design objectives. Unfortunately, none of these benefits can be quantified on the basis of experience to date.

The flight-test component of the current development plan is unlikely to yield conclusive evidence on the value of the EDS; too few aircraft and flying hours are involved. Moreover, the plan's narrow focus on hardware omits expedient consideration of EDS as an operating system, including software and data-processing needs. Before the EDS is committed to flight test, the scope of the program should be broadened to include consideration of the valuable long-term contribution that continuous recorded data can make to engine designers. It is particularly important to provide a means for determining the correlation between testing and operational duty cycles for the engines in the F-15 and F-16 aircraft. The mission profiles of these two aircraft will be quite different and their engines, although models of the F100, will be subjected to different use and should therefore be tested to the *relevant* duty cycles. Such information should help the Air Force in its component improvement program for the F100 engine, as well as in future engine design programs, especially now that reliability, durability, and cost issues are almost on an equal footing with performance objectives.

We believe that the Air Force should continue to develop a turbine engine monitoring system for the F100 engine but recommend that it take certain actions before committing a quarter of a billion dollars (1977 $) to outfit all F-15 and F-16 aircraft with EDS. First, we recommend that a flexible phased-implementation schedule be devised

that will expand the test program and defer a full-scale production go-ahead. Second, for both the F-15 and F-16 applications, we recommend that a continuous recording option be developed to provide the necessary design data and that a small staff be dedicated to analyzing these data. Third, we recommend that the life-cycle analysis be revised to provide a more realistic estimate of the costs and benefits for various EDS options.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to the following persons: *EHMS Program*--Captain J. Gissendanner, USAF; Captain T. Klimas, USAF; Sergeant F. M. Scott, USAF. *MADARS Program*--Captain R. Guy, USAF; Chief Master Sergeant T. J. Butler, USAF; Senior Master Sergeant R. M. Creasy, USAF; Senior Master Sergeant J. Haggerty, USAF. *IECMS Program*--Mr. Andrew Hess, Naval Air Systems Command; Mr. L. R. DeMott, Allison; Mr. D. Malott, Allison. *AIDS Program*--Mr. F. Miller, TWA. *EUMS Program*--Mr. R. Holl, British Ministry of Defence. *F-16 Program Office*--Captain K. Echols, USAF. *F100 EDS Program*--Major B. Carlson, USAF. Their willingness to provide data and share insights made the analyses described here possible. Dr. E. E. Covert of the USAF Scientific Advisory Board thoughtfully reviewed an earlier draft of this report. Within Rand, J. P. Large and W. H. Krase gave generously of their time in reviewing an earlier draft. S. Binnings, B. D. Bradley, S. Drezner, K. Marks, H. G. Massey, and G. K. Smith were all particularly helpful. Their substantive comments and considerable patience are much appreciated. Of course, all errors of commission or omission reside with the authors.

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I. INTRODUCTION

During the past several years, Rand has been studying methods and applications of life-cycle analysis for the United States Air Force. Life-cycle analysis of weapons systems programs requires consideration of the *benefits*, which cannot always be fully quantified (and in the military certainly not in the same metric as cost), as well as the *costs*, which appear in most cases to be more readily quantifiable. Our overall research objectives are (a) to improve the analytical methods applicable to life-cycle analysis and (b) to assess and improve the scope and richness of information provided to high-level decision-makers in support of life-cycle analysis studies and recommendations. Several recent Air Force programs in which life-cycle analysis was a major feature were selected as examples for our research. One of these exemplary programs, the F100 Engine Diagnostic System (EDS), is the topic of this briefing report.

In presenting the briefing, we tried to combine features of the broader methodological objectives of life-cycle analysis with specific applications relevant to the ongoing F100 EDS program. Thus, our presentation had two objectives: (1) to discuss some life-cycle analysis issues, and (2) to present findings that apply directly to the F100 EDS program. One issue, for example, concerns the potential long-term benefits of the EDS that are applicable to the F100 but have not been considered previously.

APPROACH TO THE STUDY

The analytical approach used in this study was to examine the experience of several selected engine monitoring systems, and then use that information as a basis for evaluating the F100 EDS.* The scope of the briefing is outlined in Fig. 1. We will review the F100 EDS to provide a background and context for the findings obtained from our

*A Rand report now in preparation describes in greater detail the supporting research on experience gained from selected engine monitoring systems.

OUTLINE

- DESCRIPTION OF F100 EDS PROGRAM
- REVIEW OF SELECTED EXPERIENCE
  - U.S. ENGINE MONITORING EXPERIENCE
  - U.K. ENGINE MONITORING APPROACH
  - ENGINE DUTY CYCLE STUDIES
- FINDINGS
- IMPLICATIONS FOR F100 EDS PROGRAM
  - COST ESTIMATES
  - DEVELOPMENT PLAN
  - DESIGN OBJECTIVES
- CONCLUSIONS AND RECOMMENDATIONS

Figure 1

examinations and analyses of the selected engine monitoring systems. The systems examined included: (1) Time Temperature Recorder (TTR), (2) Engine Health Monitoring System (EHMS), (3) Malfunction Detection Analysis Recording System (MADARS), (4) Inflight Engine Condition Monitoring System (IECMS), (5) Airborne Integrated Data System (AIDS), and (6) Engine Usage Monitoring System (EUMS).[*] The EUMS is a British system that has a different focus from that of the U.S. systems. Recent research on engine duty-cycle analysis was also examined.[†] Engine duty-cycle analysis is of particular interest because it has a significant effect on engine design and testing. The findings derived from both the monitoring system experience and the duty-cycle analysis will be discussed in terms of their implications for the F100 EDS.

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[*] The details of these case studies are given in Refs. 1 through 16.

[†] See Refs. 13, 17, and 18.

Previous F100 EDS studies have focused mainly on net life-cycle cost savings, obtained through estimated reductions in maintenance labor, spare parts, and fuel usage, as justification for developing the system.* The intent here is not to challenge the cost-estimating procedure in general, or any particular cost value used in the life-cycle cost calculations, but rather to focus on the comprehensiveness of the cost elements considered, the expectation of achieving the net cost savings estimated, and the type of information presented to high-level decisionmakers leading to the EDS decisions. Along with the cost estimate, the F100 EDS development plan and its design objectives were also examined.

In these three areas (design objectives, development plan, costs), there are substantial problems because the original formulation of the F100 EDS concept did not take advantage of lessons learned from previous monitoring experience. This, in turn, led to an incomplete and perhaps potentially misleading estimate of life-cycle costs.

The body of this report provides the rationale for our conclusions and recommendations. Substantive changes to the program are recommended. Fortunately, the program is in its infancy, and important decision points affecting its development and procurement still lie ahead.

THE F100 EDS PROGRAM

The F100 engine is the most advanced and most expensive fighter engine in use today. It is of modular design, and the USAF intends to employ the "on-condition maintenance" concept in managing the engine, i.e., to perform maintenance based on positive identification of condition rather than an operating time limit.† This represents a marked change from the present "hard time" maintenance approach, i.e., maintenance performed at fixed operating time intervals. For "on-condition maintenance" to work effectively, the condition of the engine must be known with a much improved degree of precision, and the relationship between engine parameter trends and failure modes must be established. The F100 EDS program (Fig. 2) grew out of this need to develop new

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*See Ref. 19.

†For a more complete discussion, see Ref. 20, pp. 57-59.

DESCRIPTION OF F100 EDS PROGRAM

DESIGN OBJECTIVES:
- INCREASE AIRCRAFT SYSTEM AVAILABILITY/RELIABILITY
- REDUCE LIFE CYCLE COST
- IMPROVE MANAGEMENT OF F100 ENGINE PROGRAM

DEVELOPMENT PLAN:
- CURRENTLY IN ENGINEERING DEVELOPMENT LEADING TO FLIGHT TEST DEMONSTRATION
  - 5 F-15s (10 MONTHS)
  - STARTS JAN '79
  - COMPLETION NOV '79
- PRODUCTION DECISION EXPECTED EARLY IN 1980

SCOPE:
- EQUIP ALL F-15s & F-16s (2000 AIRCRAFT/3000 ENGINES)
- RDT&E AND PROCUREMENT COST $280 MILLION ($1977)

Figure 2

propulsion operations and maintenance procedures and management practices while reducing support costs.* Because of this need, the Air Force established design objectives for the EDS that are intended to benefit the F100 engine by collecting inflight engine data.

The EDS derives data from about 40 engine sensors designed to measure pressures, temperatures, speeds, control positions, and vibration. Additional airframe sensors provide data on altitude, angle of attack, airspeed, fuel flow, and other relevant parameters. The data are recorded in two modes. In the first mode, the EDS employs a snapshot recording of inflight data. Engine and airframe data are continuously monitored and stored for the preceding 5 seconds. An out-of-limit event triggers data recording for the 5-second period immediately preceding the event and for 2 seconds afterward. The system also records snapshot data at predetermined mission windows

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*Reference 21 provides insight into the potential maintenance benefits as perceived by the user, the Tactical Air Command.

(altitude/Mach number sustained for a specific period of time) for postflight analysis and the trending of data. These data are intended to permit the trending of engine characteristics and the diagnosis of engine problems. In the second mode, the EDS cumulatively counts and records major engine cycles and time above specified critical temperatures. More accurate estimates of the remaining useful life of engine parts and better inventory and maintenance management are anticipated.

The F100 EDS program, currently in engineering development, will lead to a demonstration program on five F-15s flown for a 10-month period. The flight-test demonstration is expected to be completed in November 1979, and to be followed by a production decision in early 1980.* This plan is central to certain important points that we will make regarding lessons learned from previous experience.

The scope of the F100 EDS program is large. It involves all the F-15 and F-16 tactical fighter aircraft, and affects approximately 2000 airframes and 3000 F100 engines. The RDT&E and procurement costs for the EDS are estimated to be about $280 million (FY1977 dollars). The current Air Force life-cycle analysis suggests that if the stated design objectives are met, the F100 EDS investment costs will be fully recovered through net savings of outyear engine recurring support costs during the useful life of the engine.

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*As of October 1978; more recent information indicates that the schedule is expected to change.

II. SELECTED CASE STUDIES

The selected case studies, shown in Fig. 3, reflect Air Force, Navy, commercial, and British applications of engine monitoring systems. The systems were applied to engines for U.S. military fighter, attack, trainer, and cargo aircraft, commercial transports, and a spectrum of British aircraft. Applications include both single-pilot and multi-crew aircraft and single-engine and multiengine designs.

CASE STUDIES

SYSTEM	AIRCRAFT/ENGINE	COMMENT
TIME TEMPERATURE RECORDER (TTR) SEPT 67 - JAN 69	F-100/J57	SINGLE PARAMETER MEASUREMENT; CONUS & VIET NAM EXPERIENCE (CONTROL GROUP)
ENGINE HEALTH MONITORING SYSTEM (EHMS) JULY 76 - MAY 77	T-38/J85	FLEET RETROFIT NOT RECOMMENDED (CONTROL GROUP)
MALFUNCTION DETECTION ANALYSIS RECORDING SYSTEM (MADARS) LATE 60's - PRESENT	C-5A/TF39	CONTINUOUS RECORDINGS USED TO EXTEND TF39 TBO AND FOR CONFIGURATION MANAGEMENT
IN-FLIGHT ENGINE CONDITION MONITORING SYSTEM (IECMS) 1973 - PRESENT	A-7E/TF41	USEFUL FOR OPERATIONS & COMPONENT IMPROVEMENT PROGRAM: STILL IN DEVELOPMENT (NO CONTROL GROUP)
AIRBORNE INTERGRATED DATA SYSTEM (AIDS) LATE 60's - PRESENT	COMMERCIAL WIDEBODIES	LIMITED APPLICATIONS; RETROFIT NOT COST EFFECTIVE
ENGINE USAGE MONITORING SYSTEM (EUMS) EARLY 70's - PRESENT	U.K. AIRCRAFT	INTENDED TO REDUCE FUTURE LCC THROUGH IMPROVING ENGINE DESIGN

Figure 3

The monitoring systems themselves ran the gamut of parameter measurement—the TTR system measures only a single parameter, whereas IECMS measures in excess of 60 parameters. Most of the systems used snapshot recording, very much like the F100 EDS; others recorded data

continuously. The operational focus of the monitoring systems was also varied. The U.S. systems are oriented primarily toward improving day-to-day maintenance, whereas the British system ignores the short-term maintenance benefits, choosing rather to emphasize the longer-term feedback of operational data to the design and test communities. An identified control group existed for several of the monitoring systems. Unfortunately, the control groups did not control for all the variables of interest, and the time interval for most tests was too short to stabilize inputs and quantify some of the possible outcomes. Nevertheless, although all the information desired isn't available, much useful information was obtained.

The study described here drew upon the experience from all the case studies, but for this summary report we have selected two case studies as illustrative examples: the EHMS on the T-38 because it is the U.S. AF system that most closely resembles the approach taken by the F100 EDS, and the British EUMS because the approach taken is entirely different from that of the U.S. systems. These studies will be discussed below.

THE T-38 EHMS CASE STUDY

The T-38 EHMS is the Air Force system most similar to the F100 EDS. It emphasizes improved day-to-day engine maintenance. Engine health data are stored only under the following three conditions: (1) when engine parameters exceed normal limits, (2) on pilot command, and (3) under preprogrammed flight conditions. When any of the three conditions occur, all parameter data as of that moment are recorded (snapshot recording). Program data were obtained for the test that was conducted from July 1976 to May 1977.* Two groups of engines were used in the test: an instrumented group and a control group (see Fig. 4). The two groups contained the same number of engines and were used for approximately the same number of flight hours. Statistical testing detected no significant difference in time since last overhaul or in flight-hour distributions among the engines of both groups.

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*The data for the instrumented and control engines are summarized by engine serial number in Ref. 11. Individual engine malfunction report data were obtained from the Program Office.

EHMS (T-38 / J85) ACTIVITY OUTCOMES

JULY '76 – MAY '77

	INSTRUMENTED ENGINES	CONTROL ENGINES
NUMBER OF ENGINES	26	26
TOTAL FLIGHT HOURS	6226	6443
MALFUNCTION REPORTS	97	48
GROUND MAINTENANCE		
UNSCHEDULED REMOVALS	53	23
TROUBLESHOOTING (MH)	169	90
REPAIR (MH)	1403	530
ENGINE GROUND RUNS		
TROUBLESHOOTING	52	38
TRIMS	26	14
FUEL USED (GAL)		
TROUBLESHOOTING	4846	1786
TRIMS	5720	4480

Figure 4

Twice the number of malfunctions were reported for the instrumented engines as for the control engines. This resulted in a larger number of malfunction reports, which, in turn, increased the number of unscheduled engine removals, troubleshooting and repair manhours, the number of ground runs, and the amount of fuel used for troubleshooting and trimming the engines. Examination of the malfunction reports revealed, however, that the EHMS flagged only five malfunctions out of a total of 97, independent of pilot and maintenance crew reports.* From discussions with those involved in the test,† and an analysis of the data, we conclude that the increased number of malfunction reports resulted from increased sensitivity on the part of the pilot and maintenance crew. Both pilot and maintenance crew knew that the system

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*More recent data from F-5 experience at Holloman AFB, where the mission profile is more severe, indicate that the system finds more engine problems independently.

†See Ref. 1.

was on the aircraft, and their behavior was affected by that knowledge. Although the EHMS reported few malfunctions independently, it did provide information that significantly improved the cause-and-effect understanding of engine problems encountered and that was useful in providing maintenance direction to the ground crews.

It is interesting to note that the J85 was a mature engine and that the number of engine problems encountered was not very great. Also, the EHMS was not a new system, having been through a feasibility phase during December 1972 and January 1973. Nevertheless, hardware and software problems in the EHMS caused schedule delays. A 6-month delay was necessary to shake down the installation and software. The shakedown not only lowered the false-alarm rate but also reduced the EHMS maintenance manhours per flight hour below the number deemed necessary for day-to-day operation.

The EHMS Program Office had anticipated that less maintenance, less fuel, and fewer problems would result in all the categories shown in Fig. 4, but more manhours and fuel were actually required, resulting in higher cost. Confusion exists as to the costs and benefits that might reasonably be expected from an engine diagnostic system. All the potentially important system and engine benefits--improved readiness, availability, reliability, and lower intermediate and depot maintenance costs--were not demonstrated because the controls necessary to the collection of data appropriate for analysis were not maintained over a sufficiently long test period. Current objectives of monitoring systems are oriented to *cost-reduction*, and the lack of control for certain potentially important variables results from a lack of emphasis on noncost benefits. In spite of the additional unscheduled engine removals, maintenance manhours, and fuel used, no measurable positive output--i.e., no cost savings and no increase in readiness or availability--was discernible from the EHMS experience. Perhaps the engine's maturity and the shortness of the test explain the lack of positive outputs.

THE BRITISH EUMS CASE STUDY

The British system (see Fig. 5) purposely ignores the short-term

U.K. APPROACH — ENGINE USAGE MONITORING SYSTEM (EUMS)

OBJECTIVES:
- IMPROVE UNDERSTANDING OF ENGINE DUTY CYCLE/MISSION

APPROACH:
- INSTRUMENT SMALL SAMPLE OF EACH TYPE AIRCRAFT
- RECORD PARAMETERS CONTINUOUSLY
- UTILIZE DEDICATED ENGINEERING STAFF
- ANALYZE DATA BY MISSION TYPE

EXPECTED BENEFITS:
- ENGINE DESIGN
- CORRELATE TEST/DUTY CYCLES
- MAINTENANCE
- RELIABILITY
- COMPONENT IMPROVEMENT PROGRAM (CIP)

Figure 5

maintenance-oriented benefits; instead, the British choose to concentrate on perfecting their *engineering understanding* of the engine operating environment and to use this understanding to improve present and future engine designs. The system's primary objective is to improve safety and availability and ultimately to reduce life-cycle cost.

The focus of the EUMS reflects two conclusions that the British reached in the late 1960s and early 1970s when they experienced a spate of engine problems coupled with rising operating and support costs. Preliminary investigations revealed that the problems occurred because the engine's operational environment was not completely understood.* Subsequent studies concluded that a system that would provide a continuous recording of a few parameters was the simplest, cheapest, most reliable, and most productive solution available, given the

*The EUMS is also partially a result of the difficulty that the British had in understanding how the Rolls Royce Spey engine could be so successful in the F-4K interceptor, and in a modified version (the TF41) this engine could be so troublesome in the A-7E attack aircraft.

prevailing state of the art. This conclusion was also influenced by the fact that despite the investments made by the U.S. in complex monitoring programs, there was not a single one that, the British felt, had explored the full potential of engine health monitoring.*

The British proceeded to develop a continuous recorder that would record a small number of engine parameters. For example, on the Harrier engine, only eight parameters are recorded. This equipment is being installed on a few of each type of aircraft now in operation. The field data are sent directly to a central location, where they are analyzed by a dedicated engineering staff consisting of engineers from the Ministry of Defence and from the testing community, as well as by engineers from Rolls Royce.† Analyzed by mission type, these data have yielded interesting and important observations. The British have found, for example, that the amount of engine life consumed depends, to an important extent, on the type of missions flown and how the equipment is used during the mission. They also found that a major contributor to reduced engine life is the cumulative effect of small power transients. They have concluded--and the U.S. military services are also reaching the same conclusion--that engine failure modes, such as low-cycle fatigue, have not been as well understood as they were thought to be. Quantitative engineering data are now being used to improve engine design specifications and to bring both full-scale and component test cycles in line with operational duty cycles. The British are in the process of reorienting their approach to maintainability and reliability, recognizing that these areas are more a function of engine throttle cycles experienced and the type of mission flown than of flying hours only.

ENGINE MONITORING SYSTEM OUTCOMES

To evaluate the strengths and weaknesses of previous monitoring systems, we divided system objectives into two groups based on a time

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*See Refs. 6, 7, and 9 for a complete discussion of the EUMS objectives and approach.

†The British method of handling data is designed for an engineering study. For day-to-day maintenance purposes data must be used at the squadron level in the field. This is an important distinction.

orientation: (1) short-term operations, maintenance, and management and (2) long-term design. Figure 6 lists the characteristics that we feel are desirable in a monitoring system. Certain of these characteristics served as design objectives for each of the case studies. For example, as a result of engine system monitoring, EHMS expected fewer maintenance manhours, a savings in fuel, fewer parts consumed, and fewer unscheduled engine removals.*

SUMMARY OF ENGINE MONITORING SYSTEMS OUTCOMES

MAINTENANCE ORIENTED

- OPERATIONAL
  - AWARE OF ENGINE HEALTH
  - AWARE OF ENGINE OVERTEMPERATURES
- MAINTENANCE
  - √ LESS MAINTENANCE MANPOWER
  - √ LESS TROUBLESHOOTING & TRIM FUEL
  - √ LESS ENGINE REMOVALS
  - √ LESS PARTS CONSUMPTION
  - ANTICIPATE MAINTENANCE (TRENDING)
  - IMPROVE CAUSE & EFFECT UNDERSTANDING
  - VALIDATE MAINTENANCE ACTION
- MANAGEMENT
  - √ MODIFY TBO
  - PROVIDE CONFIGURATION CONTROL

DESIGN ORIENTED

- GUIDE CIP
- CORRELATE TEST/DUTY CYCLES
- AID FUTURE ENGINE DESIGN

Figure 6

Since the primary design objective of most monitoring systems is to reduce resources, the five outcomes noted by checkmarks in Fig. 6 have received the most attention because it is easier to cost them.

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*The background of EHMS and details of the benefits expected from engine monitoring are discussed in Ref. 11.

Given sufficient information, all characteristics could be assigned values. The first four characteristics were important in providing justification for the F100 EDS, but all of them must be considered because, in some cases, the unchecked characteristics may justify the costs of a new monitoring system.

To show the outcome of each monitoring system, we employ the matrix shown in Fig. 7. (The EDS column will be filled out in Fig. 10.) The coding used in Fig. 7 requires some explanation.

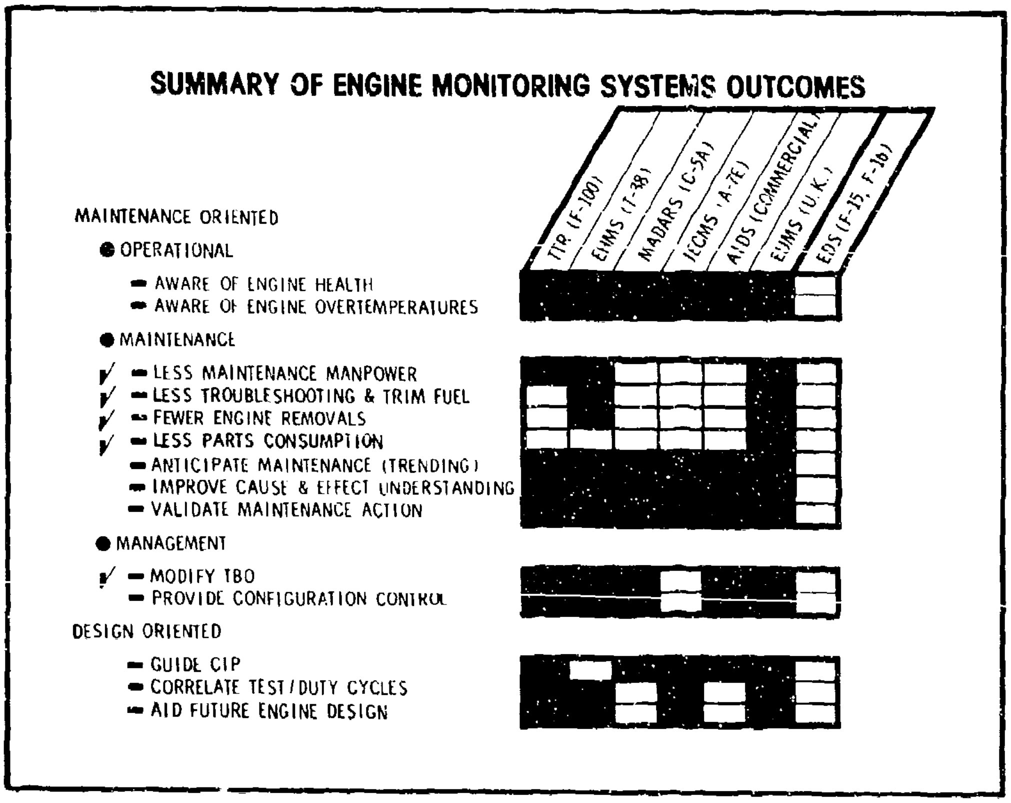

Figure 7

The red coding means that the particular characteristic was not achieved; but we must point out, however, that in many cases it was not a design objective and no attempt was made to achieve it. The yellow coding signifies that the information necessary to determine

if the monitoring system did or did not accomplish the characteristic is lacking. The green coding indicates that the characteristic was achieved or was beginning to be achieved. Several of the green blocks are crosshatched to indicate that the benefits existed but additional explanation is required.

Moving down the EHMS column, we see that both operational characteristics were achieved. Becaused overtemperature damages the most critical and most expensive engine components, this information is extremely important. Our research on engine overtemperatures in fighter and attack aircraft shows that pilots report only about one-third of the significant engine overtemperatures and are unable to report overtemperature duration. This is to be expected, because these aircraft are mostly single-crew aircraft, and the pilot sits in a small, crowded, vibrating cockpit with a number of small gauges. His attention must be divided among many functions, whereas the monitoring system watches engine parameters full time.

For the EHMS, the first three characteristics under maintenance are coded red because the instrumented engines consumed more maintenance manhours, troubleshooting, and trim fuel, and experienced a higher removal frequency, than the control group engines during the flight-test evaluation. The parts-consumption block is colored yellow because no data were collected.

The last three characteristics under maintenance are colored green because they were just beginning to be achieved, but achievement requires time to develop fully. Looking at the lower left-hand corner of the matrix, we see that the management and the long-term design-oriented blocks for both the TTR recorder and the EHMS are red. Although the EHMS was not intended to achieve the long-term benefits, we think that the matrix is also telling us that when a diagnostic system is applied to a mature engine, it does not have an opportunity to make a substantial impact in these two areas. This is because the engine is well understood and most of the problems have been corrected, or its service life is considered satisfactory.

In contrast, MADARS, IECMS, and AIDS were all installed either as original equipment or very early in engine life. Each system records

internal gas temperatures and pressures. Since all of them provide the operator with an awareness of engine health, these blocks are coded green. Under maintenance, however, the first four characteristics are coded yellow because either all of these engines are instrumented or there never has been an identified control group.

The improved awareness and understanding provided by the monitoring systems has an important effect on the last three maintenance objectives. Three examples are: (1) In the case of hard time maintenance procedures, the data can be used to study engine parameter trends. Some maintenance problems can then be alleviated by using a different maintenance schedule. (2) The data will improve the maintenance crew's understanding of engine malfunction cause and effect, permitting the crew to work smarter rather than harder. (3) The data can be used to avoid a shotgun approach to maintenance in which good parts are needlessly replaced.

Unfortunately, it takes time to fully achieve these benefits. Experiencing engine failures, and reviewing the data leading up to the failures, precedes any attempt to correlate a particular engine parameter's trend with an incipient engine failure. Only when such correlation exists can the operations, maintenance, and management personnel make use of this information to schedule or initiate maintenance.

In the case of modifying the Time Between Overhaul (TBO) for the MADARS, the crosshatched green block indicates that the monitoring system data provide one of many inputs that constitute the information set enabling TBO to be extended. The technical data provided by the monitoring system helps to establish the proper TBO in three ways: (1) by providing additional confidence to the decisionmaking process; (2) by helping to uncover incipient failure modes that are at present undetected in C-5A fleet engines; (3) by tracking the reliability and durability of new parts and components incorporated into the engines.

For the IECMS, the green crosshatching shows that the long-term design-oriented benefits were not part of the original monitoring objectives but resulted from an engineering need to better understand engine operational use. The IECMS program developed a continuous

recording option to enhance this understanding. The continuously recorded data permitted the operational duty cycle to be correlated with appropriate testing. *This is an extremely important contribution, because unless correlation exists, operational fleet failure modes may not be reproduced in the test cell.*

The matrix, then, reveals that the U.S. monitoring systems have focused on the short-term maintenance-oriented benefits. In contrast to the U.S. systems, the British EUMS has ignored the short-term maintenance-oriented benefits, choosing instead to focus on the longer-term design, testing, and management benefits. The British system is different in a way that we think is important: it focuses on improving engine design.

ENGINE DUTY-CYCLE RESEARCH

The U.S. Navy and Air Force, independent of the British, have also experienced many severe engine problems and, from p eliminary investigations, have concluded that their engineering understanding of the engine operational environment has been inadequate. For example, the type of early information supplied to the engine manufacturer for design guidance for a new engine is shown in Fig. 8 for the Navy F-14.* The estimated power required as a function of time for the F-14 intercept mission is shown in view (a). The actual number of engine cycles that occurred on an instrumented F-14 during flight is shown in view (b), together with the resulting change in the predicted design life of certain important engine components.† Low-cycle fatigue is important because cumulative fatigue damage occurs in cyclicly loaded parts as these parts are cycled from low to maximum RPM. Current methods for calculating LCF rely on the usage rates of cycles per hour that are derived from synthetic sortie patterns.‡

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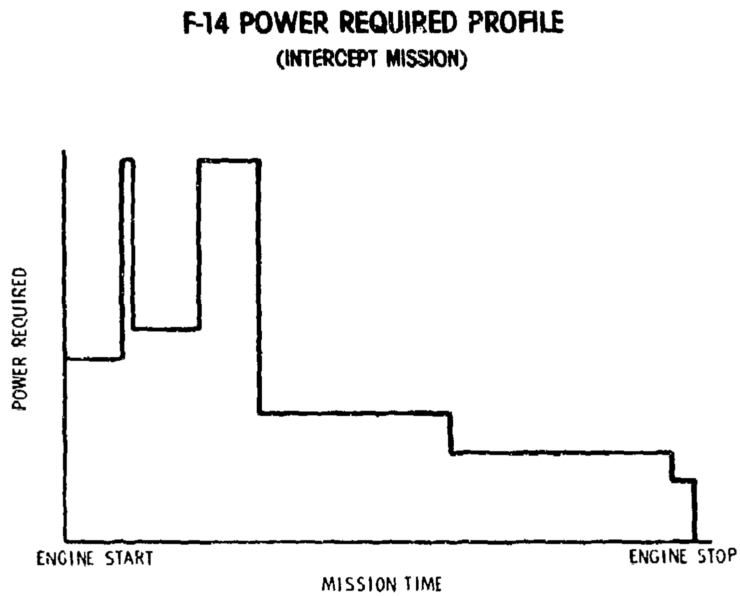
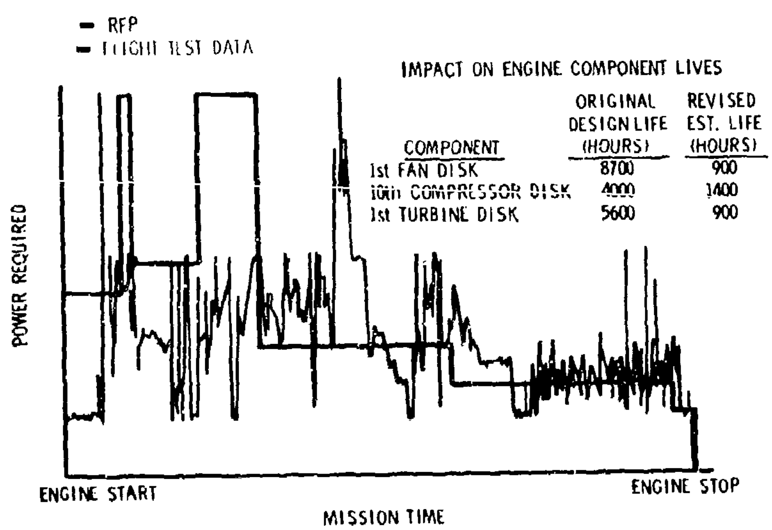
*Propulsion systems are designed to Request for Proposal (RFP) mission profiles based on a projected combat time with specific weapons load and avionics suite.

†The impact of engine duty cycle on part life and maintenance intervals is discussed in Refs. 17 and 18.

‡The sortie pattern is not the only variable. For instance, one example of recent IECMS data shows a significant difference in engine usage by a flight leader and wing man during the same mission.



(a) Estimated power (RFP) required as a function of mission time for an intercept mission.



(b) Actual power (flight test data) required as recorded on an instrumented F-14 during an intercept mission.

Figure 8

The continuously recorded flight data present a different picture for the frequency of major and minor cycles. Because the increase in the frequency of both cycles is significant and was not originally anticipated, it is contributing to engine problems. The data demonstrate the gross errors in synthetic sortie analysis and indicate that neither the service nor the manufacturer had a clear idea of the probable pattern of engine operational usage.

As a result, engine-part life has been overestimated and, hence, life-cycle costs have been underestimated. By analyzing continuously recorded data, the original estimate of engine-part life was reduced by an order of magnitude for the first fan disk (see Fig. 8b). This type of information is needed by engine designers and is only available through continuous recording. If, for example, continuously recorded data had been available from previous fighter aircraft mission experience, the F-14 powerplant, an uprated model of the TF30, might have been designed differently.

III. FINDINGS OF CASE STUDIES AND DUTY-CYCLE EXPERIENCE

Before drawing any conclusions regarding implications for the F100 EDS program, we need to summarize the findings of our case study reviews and the engine operational duty-cycle work. These findings, shown in Fig. 9, are as follows:

(1) The benefits and costs of engine monitoring are still very uncertain. Quantitative benefits have not been realized, and costs have been higher than expected. Because the control groups did not control all the variables of interest, and because the time interval for the tests was too short, we can't be definitive about the outcomes.

(2) A continuous recording system provides important design information that can be of substantial value to the Air Force, although many of the important benefits cannot now be treated quantitatively. Time is required to assimilate this information and to develop and to fully utilize the data derived from the monitoring procedure. Specific

FINDINGS – ENGINE MONITORING EXPERIENCE

- OUTCOMES FROM PREVIOUS ENGINE MONITORING APPLICATIONS ARE NOT CONCLUSIVE
- CONTINUOUS RECORDING PROVIDES IMPORTANT DESIGN INFORMATION
- MODIFICATION AFTER SOME OPERATIONAL USE ALMOST ALWAYS DESIRABLE
- MONITORING SYSTEMS DO PROVIDE AWARENESS OF ENGINE HEALTH
- MONITORING TENDS TO INCREASE EARLY SUPPORT COSTS
- SEVERAL DEVELOPMENT PROGRAMS DOMINATED BY HARDWARE AND SOFTWARE PROBLEMS

Figure 9

action will be necessary if we are to obtain certain long-term benefits. The maximum utility of the monitoring process occurs early in an engine's life when an opportunity still exists to affect engine component redesign and to give direction to the component improvement program.

(3) Improvements in the EDS design should evolve as we gain experience with the system.

(4) Monitoring systems provide the engine design and test community and maintenance crew with an understanding of problem causes and effects and, through corrective actions, ultimately improve the material condition of the engine. Engine overtemperatures are especially important, particularly in the case of a single-pilot and a single-engine aircraft.

(5) The increased sensitivity of pilots and ground crews to engine condition does result in more malfunction reports and consequently increases costs initially. Problems are identified and resources must be allocated to correct them. Another source of increased costs is the low reliability and high false-alarm rates experienced by most of the monitoring systems during initial operations. Together these two factors can initially result in a low system credibility, a handicap difficult to overcome.

(6) Several of the programs have been dominated by early monitoring-system hardware and software problems such as latent design deficiencies, manufacturing defects, nonavailability of key software subroutines, and logic errors in software. These problems continue to exist even after the monitoring systems have reached the field. It takes a long time to work out all the bugs, and this drives up initial support costs, especially when systems are prematurely fielded. These early problems are difficult to overcome, but, again, for both short-term maintenance and longer-term design and testing, the benefits appear significant if they can be resolved.

IV. IMPLICATIONS FOR F100 EDS

DESIGN OBJECTIVES

What does all this mean for the F100 EDS in terms of design objectives, completeness of analysis, cost estimates, and development?

Let's turn to the last column of Fig. 10, which is the matrix shown previously in Fig. 7. Based on the F100 EDS design, we would expect good coverage in the operational areas. For the first three objectives under maintenance, we would expect, initially, to require more maintenance and fuel, not less. Over the long term, the cost outcome is uncertain.

We would expect to realize those benefits that are difficult to quantify, but, as we have seen from all the case studies, they will

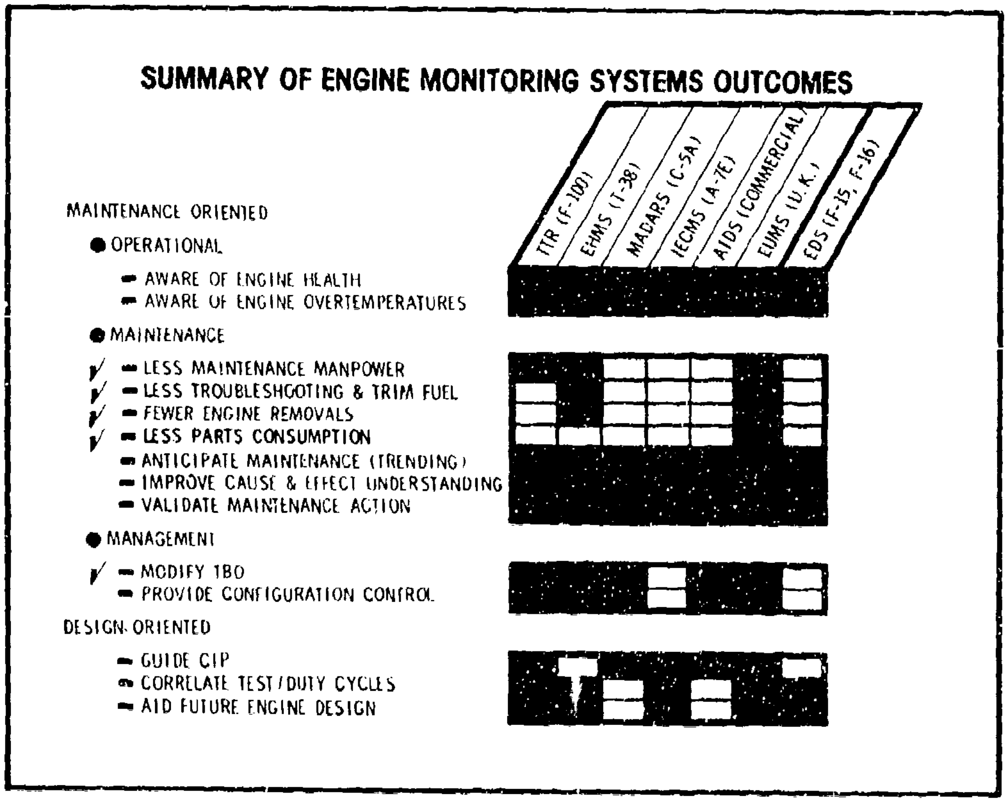


Figure 10

take time to develop. In the management area, for example, it is not clear how the hard-time limit on the life of critical parts will be affected.* As presently designed, the EDS is a snapshot recording system and, like previous U.S. monitoring systems, will not capture the long-term design-oriented benefits. Those benefits can be achieved by developing a continuous recording option.

The matrix illustrates the narrow scope of the original F100 EDS concept formulation and the follow-on life-cycle cost analysis. The information originally provided to the decisionmaker for the F100 EDS program consisted of only the first four objectives under maintenance in Fig. 10, and the decisionmaker was led to believe that all four of them would be achieved. But we have seen from experience that, initially at least, maintenance costs will increase. The long-term outcome remains undefined. That the monitoring system has the potential of contributing to design improvements, as well as to operating and support cost reductions, was not emphasized in earlier analyses. All the objectives shown in Fig. 10 represent the type of information the decisionmaker needs.

ESTIMATED COSTS AND SAVINGS

Previous F100 EDS studies have focused on the net life-cycle cost savings. In their life-cycle cost analysis, the Air Force originally addressed only the first three cost elements--RDT&E, procurement, operating and support--shown in Fig. 11. To these, data management, monitoring system improvements, and F-16 EDS modification costs must be added. The first two elements are generic to all life-cycle cost analyses and should always be considered. This problem is typical in life-cycle analysis because, usually, only some of the costs and some of the benefits are analyzed. The third element is unique to the F100 EDS program.

We find that with large, complex systems, resources required for data management can be extensive. We also find that it will be

*The F100 engine uses on-condition maintenance, where the fixed time TBO for the entire engine will be replaced by a hard-time limit on the life of critical parts and individual modules.

ESTIMATED COSTS AND SAVINGS FOR F100 EDS

LIFE CYCLE COSTS

- RDT&E
- PROCUREMENT
- OPERATING AND SUPPORT
- DATA MANAGEMENT
- MONITORING SYSTEM IMPROVEMENTS
- F-16 EDS MODIFICATION COSTS

SOURCES OF LIFE CYCLE COST SAVINGS

- FEWER UNSCHEDULED ENGINE REMOVALS
- LESS FUEL USAGE
- LESS ENGINE SECONDARY DAMAGE
- EXTENDED DEPOT OVERHAUL

Figure 11

necessary to make monitoring system improvements to increase the initially low reliability, improve sensor durability, and increase system capability. Of particular concern, however, is the fact that currently the F-16 does not have space available for the F100 EDS to fit into the aircraft. The EDS may therefore have to be repackaged or redesigned. Even though the F-16 engine is considered to be the same type/model/series as the F-15 powerplant, it may differ in an important aspect: consideration is now being given to the use of an electronic fuel control in the F-16 engine, whereas the F-15 powerplant has a hydromechanical control. This difference could result in different sensors and modifications to the F100 EDS hardware and software if the digital electronic fuel control becomes available.

IMPLICATIONS FOR COST SAVINGS

The Air Force anticipated that the acquisition cost of the F100 EDS would be more than offset by outyear engine support cost savings. The first three items shown on the lower portion of Fig. 11--fewer

unscheduled engine removals, less fuel usage, less engine secondary damage--reflect the sources of these life-cycle cost savings. Previous monitoring system experience, as shown by our case study reviews, strongly indicates that the first two items will not be realized, at least initially. Some data are just beginning to appear for the third item (engine secondary damage), and so we are unable to address it. To these three expected sources of life-cycle cost savings, a fourth, not previously considered directly, should be added. The engine monitoring system should help to extend the interval between depot overhauls. Even a small change in this interval, affecting over 3000 engines, could result in significant cost savings.

Previous studies conducted by both the Air Force and contractors indicated that the F100 EDS is expected to produce a net cost savings. The difference between the dashed line and the solid black line in Fig. 12 depicts schematically the life-cycle cost savings predicted by

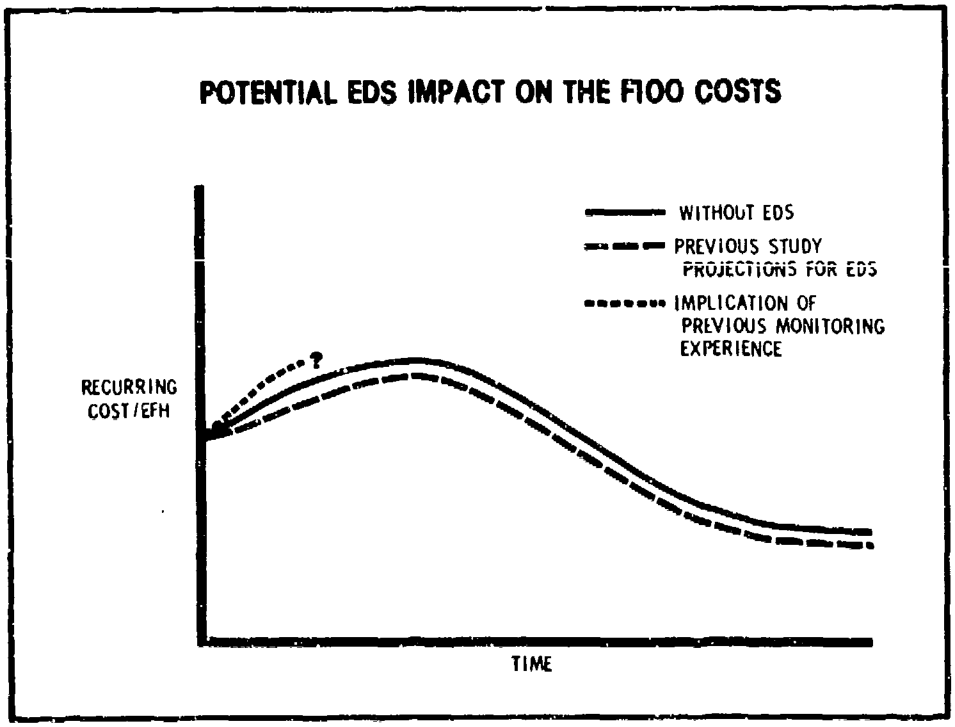


Figure 12

those studies.* However, the results from previous monitoring system experience indicate quite a different picture (short dotted line), that the cost will be greater, at least initially. There is still a great deal of uncertainty about outyear costs and whether or not they will indeed eventually fall below the solid or dashed lines. But if, for example, we can improve our understanding of failure cause and effect, and thus extend the depot overhaul interval sooner than would be possible without the EDS, reduced outyear costs can be achieved and the system may be cost effective over the long term. There is no current evidence either way. The important point is that if cost savings constitute the only criterion for EDS, it is doubtful that the F100 EDS can be justified on the basis of current information.

PROGRAM SCHEDULE

As shown by Fig. 13, important decisions regarding EDS development still lie ahead. The program is approximately 5 months behind schedule because of hardware and software problems.† A production retrofit decision is planned following completion of the flight-test demonstration sometime in early 1980. There has been some discussion, however, that the production retrofit decision will be made before the flight-test program has been completed. Once the production decision is made, the program will move into a transition phase, where the system will be redesigned to take advantage of what has been learned during the flight-test evaluation phase. Following completion of the transition phase, F-15 and F-16 EDS production and retrofit are scheduled to begin.

DEVELOPMENT PLAN

Figure 14 makes three points about the EDS development plan:

(1) Based on current F100 experience, we expect that there will be between 30 and 50 engine removals during the planned flight-test demonstration. We base this estimate on five F-15 aircraft flying 30

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*The shape of the curve in Fig. 12 is taken from Ref. 22.

†As of October 1978.

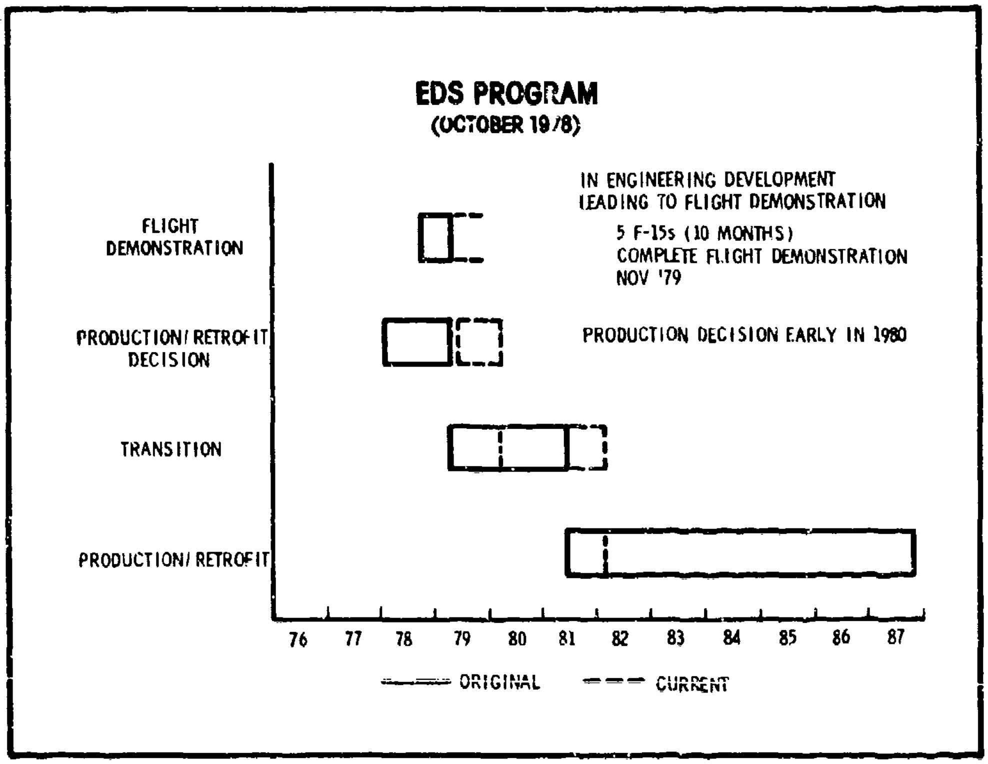

Figure 13

EDS DEVELOPMENT PLAN

- PAUCITY OF DATA
  - SMALL SAMPLE (5 F-15s)
  - TOO FEW ENGINE HOURS (300 FH/ENGINE)
- FOCUS ON HARDWARE
  - INSUFFICIENT ALLOWANCE FOR DEVELOPING DATA USAGE PATTERNS OR PRACTICES
- IMMATURITY OF ENGINE AND EDS DESIGN
  - SEVERAL ITERATIONS IN DESIGN LIKELY

Figure 14

hours a month for 10 months and on the current engine unscheduled removal rate. Some of the major complaints of the earlier monitoring systems programs were that not enough engine problems were experienced to wring out the system. We anticipate that this will be the case for the F-15 as well.

(2) For the F100 EDS to really be effective, it must operate as a system. Consideration must be given to operational software as well as to hardware, i.e., to how the data are to be used and by whom. For maintenance purposes, the data must be used at the squadron and wing level, whereas the engineering data can be processed at a central site. If data utilization for maintenance is not taken into account, the time required for EDS to become fully operational will increase.

(3) The F100 engine is a technically advanced engine and substantial improvements in reliability are possible.* In the process of trying to model this engine's mechanical and thermodynamic behavior, many things will be learned that may cause a change in the parameters monitored and thereby result in modifications to the EDS software and hardware. Thus, in all likelihood, several iterations of the EDS design will probably be necessary until the system functions as intended.

PROPOSED FUNDING PROFILE

Figure 15 shows the F100 EDS proposed funding profile for the flight-test demonstration, transition phase, and F-15 and F-16 outfitting. The RDT&E phase--previously the flight demonstration and transition phase--accounts for less than 5 percent of the anticipated program costs in then-year dollars. The remaining costs--production/retrofit--divide almost equally between the F-15 and F-16 aircraft.

The funding profile reveals a small RDT&E cost fraction, the leverage available if all the aircraft do not need instrumentation, and the short time remaining before commitment of substantial procurement funds. Since the hardware procurement and installation costs

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*Current F100 engine removal rate is greater than 10 per 1000 engine flying hours, as compared with 3 per 1000 for the J79.

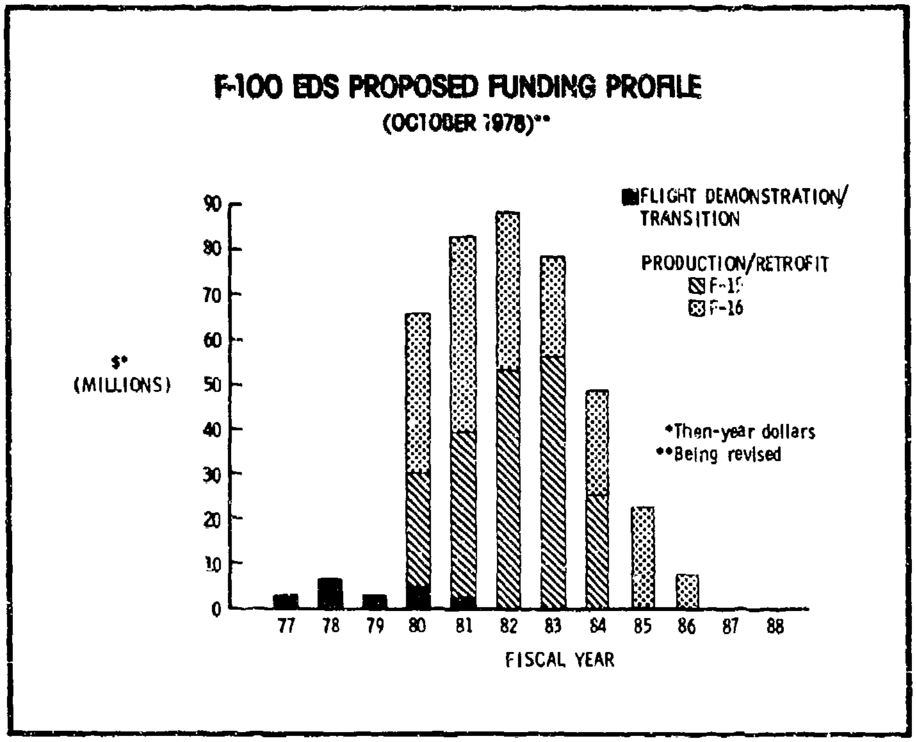

Figure 15

constitute such a large percentage of the program costs, obtaining and verifying the optimum EDS configuration and the number of aircraft to be instrumented should be of paramount concern.

CONCLUSIONS

There has never been a controlled experiment of a maturing engine over a long enough time period to allow monitoring system outcomes to be quantified. However, several conclusions can be drawn based on our case studies. These are outlined in Fig. 16.

We conclude that the maintenance cost savings used to justify the F100 EDS are unlikely to materialize over the short term. *But whether EDS passes or fails in the narrow sense of cost savings over the short term should not be the sole criterion on which EDS is judged.* Substantial value lies in the potential benefits of (a) anticipating needed maintenance, (b) helping maintenance crews and engineering

CONCLUSIONS

- EXPERIENCE DOES NOT WARRANT OPTIMISTIC NEAR TERM EXPECTATIONS
  - COSTS ARE LIKELY TO BE HIGHER
  - SUCCESSFUL EDS TAKES TIME TO MATURE
- TEST PLAN AS CURRENTLY DESIGNED IS UNLIKELY TO YIELD CONCLUSIVE EVIDENCE ON VALUE OF EDS
  - AIRCRAFT SAMPLE TOO SMALL
  - ENGINE FLIGHT HOURS TOO FEW
  - FOCUS TOO NARROW
- PRESENT SCOPE OF EDS OMITS VALUABLE LONG TERM PRODUCT
  - DESIGN FEEDBACK
  - CORRELATION BETWEEN TESTING/OPERATIONAL USAGE

Figure 16

support personnel to better understand cause and effect of engine failure, and (c) verifying that maintenance has been properly performed. These benefits are especially significant now that the Air Force is moving to an on-condition maintenance posture, as is envisioned for the F100 engine. They can also be important in helping to achieve the original design objectives of the EDS. Unfortunately, none of these benefits can be quantified on the basis of experience to date.

As currently designed, the development plan is unlikely to yield conclusive evidence on the value of EDS, because the test aircraft sample is too small and programmed flight hours are too few. In several important areas, the program focus is too narrow. For example, the software and data processing are not considered within the overall system, and the long-term design-oriented benefits are not given proper consideration.

In its present limited scope, the EDS program omits valuable long-term returns, such as, for example, long-term design feedback and improvement in test cycles. This type of information should help the Air Force in its component improvement program for the F100 engine in both the F-15 and F-16 applications, as well as in future engine design programs. It is especially important now that reliability, durability, and cost issues are almost on an equal footing with performance.

V. RECOMMENDATIONS

We recommend that the Air Force continue to develop a turbine engine monitoring system for the F100 engine but that certain actions be taken before a commitment of a quarter of a billion dollars is made to outfit all F-15 and F-16 aircraft with the EDS. These actions are outlined in Fig. 17.

RECOMMENDATIONS

- DEVELOP A PHASED IMPLEMENTATION SCHEDULE
  - NOT NECESSARILY FIXED TIME INTERVALS
  - ALLOW LONGER TEST PERIOD, MORE AIRCRAFT
  - INTEGRATE F-16 INTO PLANNING
- PROVIDE A CONTINUOUS RECORDING OPTION
  - INSTALL ON A FEW AIRCRAFT
  - STAFF A SMALL OFFICE TO ANALYZE THE DATA IN THE LONG-TERM CONTEXT
- REVISE LIFE CYCLE ANALYSIS COMPUTATIONS TO REFLECT
  - COST OF DATA MANAGEMENT, EDS IMPROVEMENTS, F-16 MODIFICATION AND INTEGRATION
  - POTENTIAL SAVINGS DUE TO EXTENSION OF OVERHAUL
  - VALUE OF MAINTENANCE AND DESIGN-ORIENTED BENEFITS

Figure 17

First, because a great deal of uncertainty exists about the cost and benefit outcomes, we recommend a flexible phased-implementation schedule that will expand the test program and defer a full-scale production go-ahead. Not only will phased-implementation maintain program flexibility, but it will also provide time to establish a control group

to control all the variables needed for a more complete understanding of the costs and benefits of monitoring the F100 engine. Hardware and software problems could then be experienced in a small sample of aircraft rather than accrue over the entire F-15 and F-16 aircraft inventory.

The additional time gained with a phased-implementation schedule could be used to reconsider the objectives of the F100 EDS program, since several of the important benefits identified in the matrix can be satisfied by instrumenting a small sample of the F-15 and F-16 inventory. This option should be included as a possibility in the decisionmaking process.

Because important differences exist between the F-15 and F-16 in both engine installation and mission flown, it is recommended that the F-16 application be fully integrated into the F100 EDS program.*

Second, the scope of the EDS should be broadened to include the valuable contribution that information feedback can make to the designer over the long term. Of particular importance is the correlation between testing and operational duty cycles for the F-15 and F-16, since their mission profiles will be quite different and the engines for each application should be tested to the relevant duty cycles. For both F-15 and F-16 applications, a continuous recording option and a small staff dedicated to analyzing the data obtained are very important. As currently designed, the EDS senses, but does not save, the data necessary for improving future engine design. A small device to save the data would be sufficient to provide the necessary design information. This device needs to be installed only on a handful of aircraft at each operational location.

Third, the life-cycle analysis should be revised to reflect more completely the costs of and benefits provided by the EDS relative to the aircraft as well as to the engine. The costs and benefits of various EDS options could then be estimated more realistically.

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*If aircraft use is changed, the operational duty cycle for the engine must be redefined, because a change in usage will cause different failure modes in the engine.

REFERENCES

1. Gissendanner, J., T. Klimas, and F. M. Scott, EHMS Program, private communications, 1978.

2. Miller, F., TWA AIDS Program, private communications, 1978.

3. *Analysis of IECMS Diagnostics & Data, August 1976-March 1977*, EDR 9175, Detroit Diesel Allison, May 11, 1977.

4. DeMott, L. R., *TF41-A-2/A7E Inflight Engine Condition Monitoring System (IECMS)*, American Institute of Aeronautics and Astronautics, No. 78-1472, August 1978.

5. *Effectiveness of a Hot Section Analyzer System as a Daily Maintenance Tool for F-100 Aircraft*, ARINC Research Corporation, January 1969.

6. Holl, R., *Development Procedures To Promote Reliability*, Advisory Group for Aerospace Research and Development, Power Plant Reliability Conference Proceedings No. 215.

7. Holl, R., and R. S. Wilkins, *The Development and Utilization of an Engine Usage Monitory System with Particular Reference to Low Cycle Fatigue*, Third International Symposium on Air Breathing Engines, Munich, March 1975.

8. Horne, E. W., et al., *Programmed Engine Maintenance: C5A Malfunction Detection Analysis & Recording System (MADARS)*, SAE Paper 700820, October 1970.

9. Hurry, M. F., and M. Holmes, *Military Engine Usage Monitoring Developments in the United Kingdom*, American Society of Mechanical Engineers, 78-GT-65, April 1978.

10. Guy, R., T. J. Butler, R. M. Creasy, and J. Haggerty, "MADARS Program," private communications, 1978.

11. Newman, Curtis E., and Michael W. Simmons, *Engine Diagnostic Effectiveness and Trending*, XRS Report 76-3-2, Hq., Air Force Logistics Command, Wright-Patterson Air Force Base, Ohio, September 1977.

12. *Performance Monitoring and AIDS Seminar/Workshop*, Vols. 1 and 2, ADI Transportation Systems, February 1978.

13. *Proceedings Fifth Annual Tri-Service Meeting on Aircraft Engine Monitoring and Diagnostics*, December 1-3, 1976, Naval Postgraduate School, Monterey, California.

14. Samuels, M., and D. V. Pauling, *Model A-7E, In-Flight Engine Condition Monitoring System (IECMS) Production Prototype Tests*, Fifth Report (Final), Technical Report SA-28R-76, Naval Air Test Center, March 29, 1976.

15. Schotta, E. A., and R. Rossenbrack, *An Assessment of IECMS Cost-Benefit*, Report No. NAILSC200-76-01, Naval Aviation Integrated Logistic Support Center, February 15, 1976.

16. *Final Report, November 1, 1972 to June 21, 1974 for U.S. Navy Inflight Engine Condition Monitoring System for A7E Aircraft with TF-41-A-2*, EDR 8275, Naval Air Systems Command, Department of the Navy, November 1976.

17. Sammons, J., and J. Ogg, *Using Accelerated Mission Testing as a Tool within the F100 Engine CIP Program*, AIAA No. 78-1085, July 1978.

18. Standahar, R. M. (ed.), *Proceedings of OSD Aircraft Engine Design and Life Cycle Cost Seminar*, Naval Air Development Center, May 1978.

19. Echols, K., and S. Binnings, *Life Cycle Cost Analysis of the Proposed Engine Diagnostic System for the F100 Engine*, F-15 Program Office, May 19, 1977.

20. Nelson, J. R., *Life-Cycle Analysis of Aircraft Turbine Engines*, The Rand Corporation, R-2103-AF, November 1977.

21. *Required Operational Capability (ROC) TAF 309-75, Jet Engine Diagnostic System*, Department of the Air Force, Headquarters Tactical Air Command, Langley Air Force Base, March 11, 1975.

22. *Report of the Procurement Management Review of Aircraft Gas Turbine Engine Acquisition and Logistics Support*, Headquarters, United States Air Force, Washington, D.C., February 1976.

23. Chopin, Matthew, and Mark Ewing, *Turbine Engine Diagnostic Monitoring Systems: A State-of-the-Art Assessment*, Technical Memorandum ENJE-TM-74-10, Analysis Branch, Propulsion Division, Directorate, Propulsion and Power, Aeronautical Systems Division.